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FOR

METHOD AND APPARATUS TO IMPROVE FREQUENCY STABILITY OF AN INTEGRATED CIRCUIT OSCILLATOR

Inventor: Giao Minh Pham

Prepared By:
BLAKELY, SOKOLOFF, TAYLOR & ZAFMAN LLP
12400 Wilshire Boulevard
Seventh Floor
Los Angeles, California 90025-1026
(206) 292-8600

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Luci M. Arevalo
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METHOD AND APPARATUS TO IMPROVE FREQUENCY STABILITY OF AN INTEGRATED CIRCUIT OSCILLATOR

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates generally to integrated circuits, and more specifically, the present invention relates to integrated circuits that are controllers for switching power supplies.

Background Information

A large class of switching power supplies operates with a fixed switching frequency. It is often desirable to know that the switching frequency will not deviate by more than a specified amount from a nominal value during normal operation of the power supply. Such knowledge is very useful to designers because it allows them to select optimum components for the power supply and for the system that must operate with it.

Designers choose a switching frequency that is suitable for the particular application. The selection of frequency depends typically on the amount of power to be processed and the topology of the power converter. Various other parameters and specifications that are important to the use of the power supply also influence the selection of its switching frequency.

The controllers for modern switching power supplies are typically integrated circuits. Some integrated circuit controllers have only one fixed switching frequency, whereas others offer the designer a choice of two or more

fixed switching frequencies. The controllers that have options for more than one fixed frequency typically allow the designer to select the desired frequency by way of a particular connection of terminals on the integrated circuit.

SUMMARY OF THE INVENTION

Disclosed are methods and apparatuses to reduce the difference between the actual frequency and the desired frequency of a simple low cost oscillator in an integrated circuit. In one embodiment, the oscillator generates a sawtooth voltage waveform by changing the voltage on a capacitor between two thresholds. The capacitor is part of the integrated circuit. Current sources add and remove electric charge on the capacitor to change its voltage between the thresholds. The frequency of the oscillator depends on the currents from the current sources that add and remove the electric charge on the capacitor. The current sources are designed with ordinary techniques for temperature compensation to reduce variations with temperature. The capacitor is coupled to the base of a first bipolar transistor, the emitter and the collector of the bipolar transistor coupled to other devices in the integrated circuit. A second bipolar transistor, substantially the same as the first bipolar transistor, is coupled to have the same base current as the first bipolar transistor. The base current of the second bipolar transistor is coupled to a current mirror circuit that adds current equivalent to the base current of the second bipolar transistor to the base current of the first bipolar transistor. Thus, the base current required by the first bipolar transistor comes from the current mirror and not from the capacitor. Hence, variations in the base current of the first transistor over the range of operating temperature do not substantially alter the charge of the capacitor to change the frequency of the oscillator.

Additional features and benefits of the present invention will become apparent from the detailed description, figures and claims set forth below.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention detailed illustrated by way of example and not limitation in the accompanying Figures.

Figure 1A is diagram that shows the general functional elements of a simple oscillator that is suitable for the controller of a switching power supply.

Figure 1B is diagram that shows the waveforms associated with the elements of the simple oscillator illustrated in Figure 1A.

Figure 2 is a diagram that shows a section of the oscillator of Figure 1A showing a how a bipolar transistor is used for the voltage follower function.

Figure 3 is a diagram showing one embodiment of a section of an oscillator in accordance with the teachings of the present invention.

Figure 4 is a diagram showing one embodiment of how a plurality of current sources can be switched to select different frequencies and duty ratios for an oscillator in accordance with the teachings of the present invention.

Figure 5 is a diagram showing one embodiment of a switching power supply with an integrated circuit controller including one embodiment of an oscillator in accordance with the teachings of the present invention.

DETAILED DESCRIPTION

An embodiment of a method to improve the stability of the nominal frequency of an integrated circuit oscillator over a wide range of nominal frequencies, temperature variations and process variations is disclosed. In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one having ordinary skill in the art that the specific detail need not be employed to practice the present invention. Well-known methods related to the implementation have not been described in detail in order to avoid obscuring the present invention.

Reference throughout this specification to "one embodiment" or "an embodiment" means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, the appearances of the phrases "in one embodiment" or "in an embodiment" in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments.

An objective in the design of integrated circuit controllers for switching power supplies is to achieve the desired performance at the lowest cost. Use of simple circuits that require the least possible semiconductor material is key to a low cost design. Therefore, it is desirable to generate all switching frequencies

with one simple oscillator circuit. It is also desirable for the oscillator to minimize the deviation of each fixed frequency from a specified nominal value over the range of operating temperature and variations in the manufacturing process.

In general, the oscillator is coupled to other circuits in the integrated circuit. Special techniques are required to prevent the variations of parameters of circuits coupled to the oscillator from altering the frequency of the oscillator without sacrificing desired performance at the lowest possible cost. Variations of parameters can occur from changes in temperature and from tolerances of the manufacturing process.

Embodiments of the present invention involve methods and apparatuses to reduce the variation in frequency of the oscillator from changes in temperature and process variations over a range of selected nominal frequencies without substantial increase in complexity or sacrifice to performance.

Figure 1A shows a typical arrangement of a simple integrated circuit oscillator that is commonly used in control circuits for switching power supplies. As illustrated, a single pole single throw switch 103 is controlled by a comparator 107. It will be appreciated by one skilled in the art that switch 103 in Figure 1A represents the function of an equivalent mechanical switch that is implemented with appropriate semiconductor devices such as for example a transistor in the integrated circuit. In one embodiment, comparator 107 is implemented with an input having hysteresis to give an upper threshold voltage and a lower threshold

voltage. The design and operation of a comparator with hysteresis will be familiar to one skilled in the art.

As shown in the illustrated embodiment, comparator 107 has an input voltage V_F on line 106 and an output voltage V_O on line 108. All voltages are with respect to the ground reference 111. The comparator 107 changes the state of its output voltage V_O from a high state to a low state when the voltage at its input 106 rises above an upper threshold V_{UTH}. The comparator changes the state of its output voltage V_O from a low state to a high state when the voltage at its input 106 falls below a lower threshold V_{LTH}. To illustrate, one embodiment of the output voltage V_O and the voltage V_F is illustrated in Figure 1B oscillating between V_{UTH} and V_{LTH}. As illustrated in Figure 1B, the voltage V_F waveform is a sawtooth waveform oscillating between V_{LTH} and V_{UTH} and V_O is a waveform oscillating between LOW and HIGH in one embodiment. The output V_O of the comparator 107 is coupled to the single pole single throw switch 103 by line 108. The switch 103 is in its open state when the voltage on line 108 is at its high state. The switch 103 is in its closed state when the voltage on line 108 is at its low state. The input to the comparator 107 on the line 106 is the voltage V_F that is also the output of voltage follower 105.

In the embodiment illustrated in Figure 1, the purpose of the voltage follower 105 is to keep the voltage V_F at its output on line 106 substantially equal to the voltage V_C at its input on line 102, while conducting negligible current 109 from the capacitor 101. The state of the switch 103 causes the voltage on

capacitor 101 to change in one of two ways. In one embodiment, the current I_0 from current source 100 is constant. It will be apparent to one skilled in the art that the current from current source 100 can be variable to change the characteristics of the oscillator for particular applications. In one embodiment, a cycle of the oscillator starts when switch 103 opens. When switch 103 is open, the current I_C 110 into the capacitor is the difference between the constant current I_O from current source 100 and the current I_B 109. Since the current I_B 109 is by design nearly constant and substantially less than the current I_O from the current source 100, the voltages V_C at line 102 and V_F at line 106 will increase at a linear rate.

When the voltage V_F at line 106 reaches the upper threshold V_{UTH} of the comparator, the switch 103 will close. When switch 103 is closed, current I_C 110 into the capacitor 101 will become negative because the current KI_O from current source 104 is greater than the current I_O from current source 100. The current KI_O from current source 104 is greater than the current from current source 100 by the ratio K. In one embodiment, the ratio K is constant. It will be apparent to one skilled in the art that in other embodiments the ratio K may be variable to change the characteristics of the oscillator to suit particular applications.

Voltages V_C at line 102 and V_F at line 106 will decrease at a linear rate until the voltage V_F at line 106 reaches the lower threshold of comparator 107, causing switch 103 to open. The cycle then repeats when switch 103 opens. The frequency of the oscillator is the rate at which the cycle repeats. Larger values of

the current I_0 will produce higher frequencies. The duty ratio of the oscillator is the fraction of one cycle that corresponds to the time switch 103 is open. For a given value of K, the oscillator will have the same duty ratio for all values of the current I_0.

In one embodiment, the voltage follower 105 includes a single NPN bipolar transistor with a current source in the emitter. Figure 2 illustrates one embodiment of a typical single transistor implementation of voltage follower 105. As shown in Figure 2, the voltage follower 200 in Figure 2 includes bipolar NPN transistor 201 and emitter bias current source 202. A single transistor implementation of the voltage follower may use either a bipolar transistor or a field effect transistor.

An advantage of using a bipolar transistor in this embodiment instead of using a field effect transistor is that a field effect transistor is generally too slow to give the desired performance. A disadvantage of using the bipolar transistor for the voltage follower is that the current I_B 109 into the base of transistor 209 usually cannot be made small enough to be negligible. The undesirable effect of current I_B 109 is that it changes the frequency of the oscillator from the desired nominal value. The current I_B 109 also changes its value significantly with temperature because it is the base current of a bipolar transistor, as will be familiar to one skilled in the art. The impacts of these undesirable effects are greater for lower frequencies of the oscillator because the current I_B 109 becomes a larger fraction of the capacitor current I_C 110 when the currents I_O and KI_O of

current sources100 and 103, respectively, are reduced to lower the frequency of the oscillator. It can be shown that the contribution of the current I_B 109 to the fractional change in frequency with respect to the desired nominal value in the embodiment of Figure 2 is

$$\frac{\Delta f}{f_0} = -\left[\left(\frac{I_B}{I_0}\right)\frac{K-2}{K-1} + \left(\frac{I_B}{I_0}\right)^2 \frac{1}{K-1}\right] \qquad \text{(Equation 1)}$$

where f_0 is the desired nominal frequency, I_B is the current 109, I_0 is the value of the current source 100, and K is the ratio of current source 104 with respect to current source 100, K>1.

In one embodiment, I_B is about 0.2 microamperes at room temperature, I_0 is 2.4 microamperes and K is 5. For these values, the presence of current I_B 109 will reduce the actual frequency from the desired nominal frequency by about 6.4% at room temperature. For larger values of K with the same I_B and I_0, the reduction in frequency approaches 8.3%. The impact of this effect will be greater at lower frequencies that use lower values of I_0. This change will be in addition to the change caused by variations in other parameters due to changes in temperature and variations in the manufacturing process. The variation in base current of a bipolar transistor can be large over the range of operating temperature, even if the emitter current is constant. It is desirable, therefore, to reduce or eliminate the influence of current I_B 109 on the frequency of the oscillator. This is accomplished by one embodiment of the present invention, as illustrated for example in Figure 3.

In one embodiment of a section of an oscillator circuit that is illustrated in Figure 3, a first voltage follower circuit 200 includes a first NPN bipolar transistor 201 and a first emitter bias current source 202. A second voltage follower circuit 300 includes a second NPN bipolar transistor 301 and a second emitter bias current source 302. In one embodiment, the second voltage follower circuit 300 is substantially the same as the first voltage follower circuit 200. Therefore, the base current I_{BF} 304 of the second voltage follower 300 in one embodiment is substantially the same as the base current I_{BF} 306 of the first voltage follower 200. The base current I_{BF} 304 is coupled to a current mirror 303. One skilled in the art will be familiar with various implementations of a current mirror, which is fundamental to the design of integrated circuits. It will also be appreciated by one skilled in the art that the second bipolar transistor 301 needs to match the first bipolar transistor 201 only in current density, and not in absolute current magnitude. The current mirror 303 and the second bipolar transistor 301 with its emitter bias current source 302 are designed such that the output current I_{BF} 305 of the current mirror 303 matches the base current I_{BF} 306 of the first bipolar transistor 201.

The output of the current mirror 303 injects into line 102 an output current I_{BF} 305, which is substantially the same as current I_{BF} 304, which is also substantially the same as the base current I_{BF} 306 of the first voltage follower 200. Since the net input current I_B 109 is the difference between the substantially equal currents 305 and 306, the current I_B 109 is substantially zero. The reduction of

current I_B 109 to zero effectively eliminates its undesirable influence on the performance of the oscillator, and permits the use of the low cost bipolar transistor solution for the voltage follower function in accordance with the teachings of the present invention.

One skilled in the art will recognize that the magnitude of the current of current source 100 and current of current source 104 can be adjusted independently to change the frequency of the oscillator. One skilled in the art will also recognize that the ratio of the current of current source 100 to the current of current source 104 can be adjusted to change the frequency and the duty ratio of the oscillator. In one embodiment, different frequencies and duty ratios are selected by the addition and removal of current sources as shown by example in Figure 4.

To illustrate, Figure 4 is a diagram showing one embodiment of how a plurality of current sources can be switched to select different frequencies and duty ratios for an oscillator in accordance with the teachings of the present invention. As shown in the depicted embodiment, closure of double pole single throw switches 402 and 403 in Figure 4 augments the current from current sources 100 and 104, which will vary that rate at which capacitor 101 is alternatingly charged and discharged, thereby varying the frequency and/or duty ratio of the oscillator. The oscillator operates at its lowest frequency when switches 402 and 403 are both open. Four distinct frequencies and duty ratios of the oscillator are possible with the example shown in Figure 4. One skilled in the art will

appreciate that additional current sources and switches may be used to achieve a greater number of frequency and duty ratio options. It will also be apparent to one skilled in the art that the addition of multiple current sources to a single current source is functionally equivalent to a change in the magnitude of a single current source. Therefore, in one embodiment, current source 410 may be considered a single variable current source comprised of current sources 100, 400 and 401 and switches S1 and S2 while current source 411 may be considered a single variable current source comprised of current sources 104, 404 and 405 and switches S1 and S2.

In yet another embodiment, an oscillator may be included in an integrated circuit that controls a switching power supply in accordance with the teachings of the present invention. To illustrate, Figure 5 is a diagram of one embodiment of a switching power supply with an integrated circuit controller including one embodiment of an oscillator in accordance with the teachings of the present invention. An unregulated direct current (DC) input voltage V_{IN} 500 is converted to a regulated DC output voltage V_{OUT} 502 by a switching converter 501 that is controlled by an integrated circuit 517. All voltages are with respect to the ground reference 111. The state of a single pole double throw power switch S_P 503 is controlled by the signal PWM_{OUT} 507 from the integrated circuit 517.

In operation, switch S_P 503 couples the inductor 504 to the input voltage V_{IN} 500 when PWM_{OUT} on line 507 is high. Switch S_P 503 couples one end of the inductor 504 to the ground reference 111 when the signal PWM_{OUT} on line 507 is

low. A capacitor 505 is coupled to inductor 504 and filters the alternating current (AC) current in inductor 504 to provide a substantially DC voltage to a load 506. In one embodiment, a sawtooth oscillator 514 included in the integrated circuit 517 is designed in accordance with the teachings of the present invention. The frequency of the sawtooth oscillator 514 within integrated circuit controller 517 determines the rate of switching.

In one embodiment, a plurality of functional terminals 511 on the integrated circuit 517 can be coupled to operate the various functions of integrated circuit 517 in a desired manner. In one embodiment, functional terminals 511 can set the frequency of the oscillator 514. Integrated circuit 517 senses the output voltage V_{OUT} 502 of the switching converter 501 at a terminal V_{SENSE} 509 with respect to a ground terminal GND 508. In one embodiment, an error amplifier 510 within the integrated circuit 517 amplifies the difference between the voltage at terminal V_{SENSE} 509 and a reference voltage 516 internal to the integrated circuit 517. A comparator 512 compares the error voltage output 513 of error amplifier 510 to the sawtooth voltage V_F 515 that is an output of the oscillator 514. The output 507 of the comparator 512 is high when the error voltage 513 is greater than sawtooth voltage 515. The output 507 of comparator 512 is low when the error voltage 513 is less than the sawtooth voltage 515. Thus, the periodic switching of power switch S_P 503 is modulated by the integrated circuit 517 in a manner to regulate the output voltage V_{OUT} 502.

It will be apparent to one skilled in the art having the benefit of this disclosure that many ways are known to implement the function of the switch S_P 503 with semiconductor devices, such as for example two transistors, or a transistor and a diode. In addition, one skilled in the art having the benefit of this disclosure will also appreciate that switching converter 501 in Figure 5 is just one example of many different circuits that are commonly used in switching power supplies that can employ an oscillator in accordance with the teachings of the present invention.

In the foregoing detailed description, the method and apparatus of the present invention have been described with reference to a specific exemplary embodiment thereof. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader spirit and scope of the present invention. The present specification and figures are accordingly to be regarded as illustrative rather than restrictive.